SIMULATION OF PROCESS PARAMETERS AND BED-HYDRODYNAMIC STUDIES FOR FLUIDIZED BED BIOMASS GASIFICATION USING ASPEN PLUS

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By

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CERTIFICATE

This is to certify that the seminar report on SIMULATION OF PROCESS PARAMETERS AND BED-HYDRODYNAMIC STUDIES FOR FLUIDIZED BED BIOMASS GASIFICATION USING ASPEN PLUS submitted by **Mohit Mohan Sahu** to National Institute of Technology, Rourkela under my supervision and is worthy for the partial fulfillment of the degree of Bachelor of Technology (Chemical Engineering) of the Institute. The candidate has fulfilled all prescribed requirements and the thesis, which is based on candidate's own work, has not been submitted elsewhere.

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Thanking you,

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ABSTRACT

Fluidized bed gasification is one of the potential sources for production of clean and eco-friendly fuel. With the gradual depletion of coal and petroleum resources biomass is being perceived as a self-sustainable source of energy production. It is cheap and readily available as well. ASPEN PLUS simulator is a strong tool for investigating the behavior of a process and it can be readily used to access various aspects like feasibility of an operation, effect of operating parameters on the performance of a gasifier. In this project work the effects of temperature, steam to biomass ratio, pressure, and equivalence ratio have been studied on the product gas composition and carbon conversion efficiency of a fluidized bed biomass gasifier. The hydrodynamics of bed materials has been analyzed considering dolomite as a testing sample with different particle diameter. Temperature was observed to be the most sensitive aspect of gasification as it is operated under atmospheric pressure. The requirement of a particular product justifies the use of steam as a gasifying agent.

Keywords: Fluidized bed gasification, biomass, ASPEN PLUS, equivalence ratio, steam to biomass ratio.

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NOMENCLATURE

η	Cold Gas Efficiency
η_{geff}	Hot Gas Efficiency
V_g	Gas Generation Efficiency
q_g	Heating Value of The Gas
M_b	Fuel Consumption Rate
C_b	Heating Value of Fuel
ER	Equivalence Ratio
SBR	Steam to Biomass Ratio
$H_{sensible}$	Sensible Heat added during Thermal Applications
d_p	Particle diameter
U_t	Terminal velocity
U_{mf}	Minimum fluidization velocity
g	Acceleration due to gravity
ρ_p	Particle density
ρ_f	Fluid density
ε	Porosity
φ	Sphericity

CHAPTER 1
INTRODUCTION

INTRODUCTION

Gasification refers to a group of processes which highlight the conversion of solid or liquid fuels into a combustible gas in presence or absence of a gasification agent. It is normally carried out by reacting fuel such as coal, biomass, oil or coke with a minimal amount of oxygen often in combination with steam. The heat liberated from the exothermic reactions of fuel and oxygen maintains the gasifier at the operating temperature and drives the endothermic gasification reactions taking place inside the gasifier. We can use steam as the gasifying agent only if we can provide an external source of heat that drags the endothermic reactions forward.

The concern for climatic variations has triggered the interest in biomass gasification making fluidized bed gasifiers as one the popular options, occupying nearly 20% of their market. Biomass being readily available, economic and carbon dioxide neutral is one the upcoming prospects for eco-friendly techniques.

Gasification definitely has certain important advantages over direct combustion. When the fuel is processed, the volume of gas obtained from gasification is significantly less as compared to that of combustion. The reduced volume of gas needs smaller equipment which results in reduced costs. Gasification definitely is an attractive option for remote locations. However one of the important shortcomings of gasification involves the reduced carbon conversion efficiency due to which a certain part of the fuel energy remains in the char.

The ASPEN PLUS process simulator has been used to simulate coal conversion, integrated coal gasification combined cycle (IGCC) power plants, atmospheric fluidized bed combustor processes, coal gasification simulation. However, the work that has been done on biomass gasification is limited. The objective of this study is to develop simulation capable of estimating the steady-state performance of a fluidized bed gasifier by considering the reaction rate kinetics. The products of homogeneous reactions are defined by Gibbs equilibrium, and reaction rate kinetics is used to determine the products of char gasification.

Table1: Some relative operational characteristics regarding gasification [1]

Parameters	Fixed/moving bed	Fluidized bed	Entrained bed
Feed size	<51mm	<6mm	<0.15mm
Tolerance of fines	Limited	Good	Excellent
Tolerance for coarse	Very good	Good	Poor
Exit gas temperatures	450-650 ^{0}C	800-1000 ^{0}C	>1990 ^{0}C
Feed stock tolerance	Low rank coal	Low rank coal and excellent for biomass	Any coal including caking but unsuitable for biomass
Oxidant requirements	Low	Moderate	High
Reaction zone temperature	1090 ^{0}C	800-1000 ^{0}C	>1990 ^{0}C
Steam requirement	High	Moderate	Low
Nature of ash produced	Dry	Dry	Slagging
Cold gas efficiency	80%	89.2%	80%
Application	Small capacities	Medium size capacities	Large capacities
Problem area	Tar production and utilization of fines	Carbon conversion	Raw gas cooling

1.1 ADVANTAGES OF FLUIDIZED BED GASIFICATION

- Air to fuel ratio can changed which also helps to control the bed temperature.
- Fluidized bed gasifiers are more tolerant to variation in feedstock as compared to other types of gasifiers.
- They maintain uniform radial temperature profiles and avoid slagging problems.
- Higher throughput of fuel as compared to other gasifiers.
- Improved mass and heat transfer from fuel.
- High heating value.
- Reduced char.

1.2 DISADVANTAGES OF FLUIDIZED BED GASIFICATION

- Oxidizing conditions are created when oxygen diffuses from bubble to the emulsion phase thereby reducing the gasification efficiency.
- Reduced solid conversion due to intimate mixing of fully and partially gasified fuels.
- Losses occurring due to particle entrainment.

The objective of this project work is to investigate the effects of operating parameters like equivalence ratio, steam to biomass ratio, temperature and pressure on product gas composition and carbon conversion efficiency of a fluidized bed biomass gasifier using ASPEN PLUS simulator. The study of bed hydro-dynamics is also carried out using dolomite as a testing sample with three different particle sizes.

CHAPTER 2

LITERATURE REVIEW

LITERATURE REVIEW

Donald L. Klass has shown that Biomass gasification processes could be divided into three categories [2]:

- Pyrolysis: if temperature is sufficiently high the primary products from pyrolysis of biomass are gases.
- Partial oxidation: they utilize less than stoichiometric amount of oxygen required.
- Reforming: conversion of hydrocarbon gases and vaporized organic to hydrogen containing compounds.

Gasification processes can be designed in such a way that the exothermic and endothermic reactions are thermally balanced. It is not possible to control the process as there is such a competition among so many reactions, hence we need proper combination of temperature, pressure, reactant and recycle product feed rates, reaction time and oxygen to steam ratio.

2.1 BASIS OF CLASSIFICATION OF FLUIDIZED BED GASIFIERS [1]

2.1.1 Gasifying Medium

On the basis of gasifying medium used, fluidized bed gasifiers are grouped into the following types:-

- Oxygen blown
- Air blown
- Steam blown

Air gasification produces a low heating value gas (5000-6000 kJ/kg, LHV) which contains diluents like 50% nitrogen. Oxygen blowing is free from diluents and has a relatively higher heating value (15000kJ/kg). Oxygen gasification demands an air separation unit for producing oxygen, while steam gasification requires an indirect source of heat for driving the endothermic reactions.

Table2: HHV of gas produced when a particular fuel is used [1]

Fuels	Higher heating value of gas produced (kJ/kg)
Air blown gasifier	5000
Oxygen blown gasifier	15000
Natural gas	55000
Water gas	23000
Coke oven gas	35000
Producer gas	5500
Blast furnace gas	2400

2.1.2 Operating Pressure Used

On the basis of operating pressure, fluidized bed gasifiers can be categorized as the following:

- Atmospheric pressure gasification
- Pressurized gasification

2.1.3 Mode Of Heating

Based on this criterion fluidized bed gasifiers can be classified as:

- Directly heated
- Indirectly heated

In a directly heated gasifier, fuel is partly oxidized to provide heat for the endothermic reactions. In an indirectly heated gasifier, heat required for gasification is supplied by a hot inert medium, which is heated by the combustion of char produced from biomass gasification in a separate reactor.

2.2 PHYSICO-CHEMICAL REACTIONS [1]

The following chemical reactions take place inside a gasifier:

- Drying (>150 ^{0}C)
- Pyrolysis or de-volatilization (150-700 ^{0}C)
- Combustion (700-1500 ^{0}C)
- Reduction (800-1000 ^{0}C)

Drying, pyrolysis and reduction absorb heat provided by the exothermic combustion process. In drying the moisture in the solid fuel evaporates. The pyrolysis or de-volatilization process separates the water vapor, organic liquids and non-condensable gases from the char or solid carbon of the fuel. The combustion reactions oxidize the fuel constituents while the gasification process reduces them to combustible gases in an endothermic reaction.

The pyrolysis process starts around 350 ^{0}C and then shoots above 700 ^{0}C. The composition of the evolved products depends upon temperature, pressure and gas composition during de-volatilization. In pyrolysis the volatile components break down and evaporate.

It can be shown by a general reaction:

Biomass + heat → char + gases + vapors or liquid

The vaporized product contains tar and other poly-aromatic hydrocarbons. The tar produced poses a major hindrance in the smooth running of the gasifier. Pyrolysis generally produces the following three products:

- Gases like H_2, CO, CH_4, H_2O, and CO_2.
- Tar, a black, viscous and corrosive liquid.
- Char, a solid residue containing carbon.

In combustion we deal with oxidation of char which practically deals with all the thermal energy needed for endothermic reactions. The following reactions take place in combustion:

$$C + O_2 \rightarrow CO_2 \qquad (1)$$

$$H_2 + 0.5\ O_2 \rightarrow H_2O \qquad (2)$$

Gasification mainly involves the following series of reactions:

- Water gas reaction

$$C + H_2O \rightarrow H_2 + CO \quad (3)$$

- Boudouard reaction

$$CO_2 + C \rightarrow 2CO \quad (4)$$

- Shift conversion

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (5)$$

- Methanation

$$C + 2H_2 \rightarrow CH_4 \quad (6)$$

2.3 COMPOSITION OF GAS YIELD [1]

The composition of gas obtained from the gasifier depends upon the following parameters:

- Fuel composition.
- Temperature
- Operating pressure
- Gasifying medium.
- Moisture content of the fuels.
- Mode of contact of reactants inside the gasifier.

2.4 EFFECT OF FEED PROPERTIES ON GASIFICATION [1]

2.4.1 Fuel Reactivity

The reactivity in gasification increases with pore volume and surface area of the feed. The particle size and porosity of feed have significant effect on the kinetics of gasification.

2.4.2 Volatile Matter

The reactivity of fuel and its conversion to char depends upon its volatile matter constitution. Fuels with high volatile matter are more reactive, produce less char and conversion to gas is easy. Biomass feedstock generally contain high amount of volatile matter although that results in high tar content which makes the clean-up very difficult.

2.4.3 Ash

The ash content doesn't decide the product gas composition but it does have a profound impact on the practical operation of the gasifier. It is an unavoidable parameter which needs to be removed in either solid or liquid form depending upon the design of the gasifiers, the temperature profile and the melting point of ash produced.

2.4.4 Moisture

The moisture content is a decisive factor for the gasification process since high moisture content of the fuels can lower the temperature inside the gasifier which can hinder the kinetics of gasification reactions which need high temperature because they are endothermic. Therefore the feedstock should have an optimal moisture content of (5-10) %.

2.5 DESIGN CONSIDERATIONS [1]

2.5.1 Gasifier Efficiency

The performance of a gasifier is often expressed in terms of its efficiency, which can be defined in two ways: cold gas efficiency and hot gas efficiency. The cold gas efficiency is used if the gas is used for running an internal combustion engine in which case the gas is cooled down to the ambient temperature and tar vapors are removed. It is defined as

$$\eta = \left(V_g * q_g\right) \Big/ \left(M_b * C_b\right) \qquad (7)$$

For thermal applications the gas is not cooled before combustion and the sensible heat of the gas is also useful. The hot gas efficiency is defined as

$$\eta_{geff} = \left(V_g * q_g + H_{sensible}\right) \Big/ \left(M_b * C_b\right) \quad (8)$$

V_g = gas generation rate (m^3/sec); M_b = fuel consumption rate (kg/sec)

q_g = heating value of the gas (kJ/m^3); C_b = heating value of fuel (kJ/m^3)

2.5.2 Equivalence Ratio

It is defined as the ratio of actual air fuel ratio to the stoichiometric air fuel ratio. An excessive low value of ER (ER<0.2) results in several problems including incomplete gasification, excessive char formation and low heating value of product gas. On the other hand if ER>0.4 then we encounter problems of excessive formation of products of complete combustion rather than the desired ones of CO and H_2. Hence we maintain an optimum equivalent ratio of (0.2-0.3). The carbon conversion efficiency increases with increase in ER value up to 0.26 after which it decreases.

2.5.3 Bed Materials

The bed material in case of fluidized bed gasifier consists mainly of inert solid particles and some fuel particles at different stages of gasification. In case of biomass gasification silica sand or magnesium oxide is used as inert bed material. The bed materials besides serving as a heat carrier can catalyze the gasification reaction by increasing the gas yield and reducing the tar formation.

2.6 PREVIOUS WORK

A .Kumar et al [3] in 2008 investigated that methane content did not vary much with change in equivalence ratio but responded significantly to change in steam to biomass ratio. The optimum value of SBR increased with temperature. High temperature favors steam reforming which reduces methane and increases hydrogen. Regression analysis has shown that temperature has a profound impact on hydrogen concentration because it provides the necessary energy for endothermic reactions favoring hydrogen production. The equivalence ratio and SBR have limited effects on hydrogen composition. The carbon monoxide content was less than 7% for most experimental conditions. Increasing SBR and equivalence ratio increased the amount of char for all levels of temperature. With increase in temperature and equivalence ratio, carbon conversion efficiency increases because it is accompanied by oxidation and breakdown of the molecular bonds in the biomass leading to higher conversion of the solid carbon to gaseous molecules. Increase in steam temperature would reduce the gasification temperature which would reduce carbon conversion efficiency. The optimum value of steam temperature is in the range of (120-150) ^{0}C. The cold gas efficiency first increases with increase in equivalence ratio until the composition of CO and H_2 reaches a maximum but after that with further increase in equivalence ratio complete combustion takes place and CO_2 and H_2 formation takes place.

A model was devised by Mehrdokht and Mahinpey[4] in 2008 in ASPEN PLUS simulator where they discussed the hydrodynamic parameters and reaction kinetics. In the simulation they used two CSTR reactors for gasification indicating the bed-zone and the freeboard zone. They used FORTRAN codes to simulate the CSTR reactors and then under various operating conditions checked the performance of the gasifier. Temperature enhanced the hydrogen production and carbon conversion efficiency. Increasing the equivalence ratio first increases the carbon conversion efficiency and then decreases after an optimum value. They also observed that increasing steam to biomass ratio increased the hydrogen production and carbon conversion efficiency. Biomass particles in the size range of (0.25-0.75) mm do not affect the product gas composition.

Philippe Mathieu and Raphael Dubuisson [5] in 2002 analyzed the performance of a fluidized bed gasifier by devising a model which was based on minimization of Gibbs free energy in ASPEN PLUS simulator. A sensitivity analysis was also carried out with respect to oxygen factor, air temperature, oxygen content in air, operating pressure and injection of steam. It was found that the reaction temperature almost doubled when oxygen factor increased from 20% to 50%. N_2 and H_2O show an increasing trend and CO and H_2 show a decreasing trend when oxygen factor was increased. CO_2 remained almost constant and CH_4 remained zero for oxygen factor in the range of 20-50%. Gasification efficiency rises when oxygen factor increases from 20-30% but it registers a fall when oxygen factor increases beyond 30%. The gasification efficiency increases significantly when air is preheated from 25 ^{0}C to 300 ^{0}C but then the increase in minimal. Pressure has an optimum value when we consider its effect on gasification efficiency. There has to be a balance in between CO, H_2 and CH_4 to achieve the maximum gasification efficiency. The injection of steam invokes a rise in the formation of CO and H_2 but it also decreases the gasification efficiency.

WenyiTAN and QinZHONG [6] in 2010 studied the effects of gasification temperature, pressure and steam to biomass ratio on hydrogen production in a biomass gasifier. Lv et al. [7] in 2003 also studied the effects of steam to biomass ratio, reactor temperature, equivalence ratio and biomass particle size on production of hydrogen rich gas during Biomass air-steam gasification. The extra hydrogen content was attributed to water gas reaction and steam reforming reactions. Further steam reforming weakens after 700 ^{0}C when Boudouard reaction and water gas reaction paly dominant role.at higher pressures hydrogen and CO decreases and CO_2 and CH_4 content increases.

A model was prepared by Paviet et al. [8] in 2009 addressing a thermochemical process occurring a wood biomass downdraft gasifier where they highlighted the effects of char conversion, air fuel ratio on temperature and product gas composition using the Redlich Kwong Soave equation of state with Boston Mathias Modification (RKS-BM). It was selected basing upon its reliable heat duty.

A.Gomez-Barea et al. [9] in 2010 emphasized char conversion and tar elimination as decisive factors for fluidized bed gasification plant because the main loss from the plant is carbon in the ash. They also concentrated on some of the existing models of char conversion like shrinking core model (SCM), Extracted shrinking core model (ECM), Grainy Pellet Model (GM) etc.

Secondly they also reviewed the empirical and fundamental models describing behavior of biomass and char particles along with comminution, kinetics and fluid dynamics.

Dayton [10] in 2002 stressed on the role of calcined dolomites as being the most widely used non-metallic catalysts for tar conversion because they are inexpensive and disposable. Lacking the strength they usually undergo attrition in fluidized bed reactors. They are operated at 900 ^{0}C to obtain high tar conversion. Paasen et al. [11] in 2004 observed a lot of difference in the amount of tar produced and composition of tar which basically depends on conditions of formation like primary tars comprising of cellulose, hemicellulose, lignin derived products, secondary tars including phenolics and olefins. Then we have the alkyl tertiary tars which are methyl derivatives of aromatics and finally we have condensed tertiary tars which are PAH (Poly-Aromatic hydrocarbons) without substituents.

CHAPTER 3

SIMULATION AND MODELING

SIMULATION AND MODELING

ASPEN PLUS simulator provides an opportunity to check the feasibility of a process, to study and investigate the effect of various operating parameters on various reactions. It is a strong tool for simulation studies and helps in analyzing the outcome of a process.

3.1 ASPEN PLUS SIMULATION

Biomass gasification models can be divided in two ways according to Pengmei LU et al. [12]:

- **Kinetic model:** here we can simulate the reaction conditions at different times and sites which will make it suitable for reactor amplification design and operation parameters optimization.
- **Equilibrium model:** it predicts only end reaction product distribution but gives no idea about the instantaneous product distribution along with geometric dimensions.

In this particular simulation we will consider both the reaction kinetics parameters and bed hydrodynamics aspects. The following assumptions were considered in modeling the gasification process:

- Process is isothermal and steady state.
- Biomass de-volatilization is instantaneous in comparison to char gasification.
- Particles are spherical and are not affected in course of the reaction, based on the shrinking core model [4].
- Char comprises only of carbon and ash.
- Char gasification initiates in the bed and ends in the freeboard.
- Liquid modeling is considered rather than solid modeling for biomass due to unavailability of certain parameters.
- The simulation is carried with power-law kinetics.
- The residence time for reactants is sufficiently high to reach chemical equilibrium.

3.2 KINETIC PARAMETERS

Table 3: Gasification reactions and their kinetic parameters [1] [4]

Reactions	Rate constant($sec^{-1}atm^{-1}$)	Activation energy (kJ/mole of carbon)
$C + H_2O \rightarrow H_2 + CO$	6474.7	13130
$CO_2 + C \rightarrow 2CO$	6474.7	17250
$CO + H_2O \rightarrow CO_2 + H_2$	6474.7	4198
$C + 2H_2 \rightarrow CH_4$	6474.7	7481
$C + 0.5\ O_2 \rightarrow CO$	0.046	110.50
$C + O_2 \rightarrow C\ O_2$	0.046	393.77

Table 4: Characteristics of pine saw dust [4]

Moisture content (%)	8
Proximate analysis (dry weight %)	
Volatile matter	82.24
Fixed carbon	17.16
Ash	0.55
Ultimate analysis (dry weight %)	
Carbon	50.54
Hydrogen	7.08
Oxygen	41.11
Nitrogen	0.15
Sulfur	0.57

3.3 ASPEN PLUS MODELLING

The different stages considered in ASPEN PLUS simulation are decomposition of the feed, volatile reactions, char gasification, and gas–solid separation.

3.3.1 Biomass Decomposition

The ASPEN PLUS yield reactor, RYIELD, was used to simulate the decomposition of the feed. In this step, biomass is converted into its components including carbon, hydrogen, oxygen, sulfur, nitrogen, and ash, by specifying the yield distribution according to its ultimate analysis.

3.3.2 Volatile Reactions

The ASPEN PLUS Gibbs reactor, RGIBBS, was used for volatile matter combustion under the assumption that volatile reactions follow the Gibbs equilibrium. Carbon partly constitutes the gas phase, which takes part in de-volatilization, and the remaining carbon comprises part of the solid phase (char) and subsequently undergoes char gasification.

A SEPARATION COLUMN model was used before the RGIBBS reactor to separate the volatiles and solids in order to perform the reactions.

3.3.4 Char Gasification

The ASPEN PLUS CSTR reactor, RCSTR, performs char gasification by using reaction kinetics.

Table 5: Experimental set up parameters used in the simulation [4]

FLUIDIZED BED REACTOR	
Temperature (^{0}C)	700-1000
Pressure (bar)	1.05
Bed diameter (mm)	40
Freeboard diameter	60
Height (mm)	1400
AIR	
Temperature (^{0}C)	65
Flow rate (m^3/hr)	0.5-0.7
STEAM	
Temperature (^{0}C)	145
Flow rate (kg/hr)	0-1.8

3.4 SIMULATION FLOWSHEET[4]

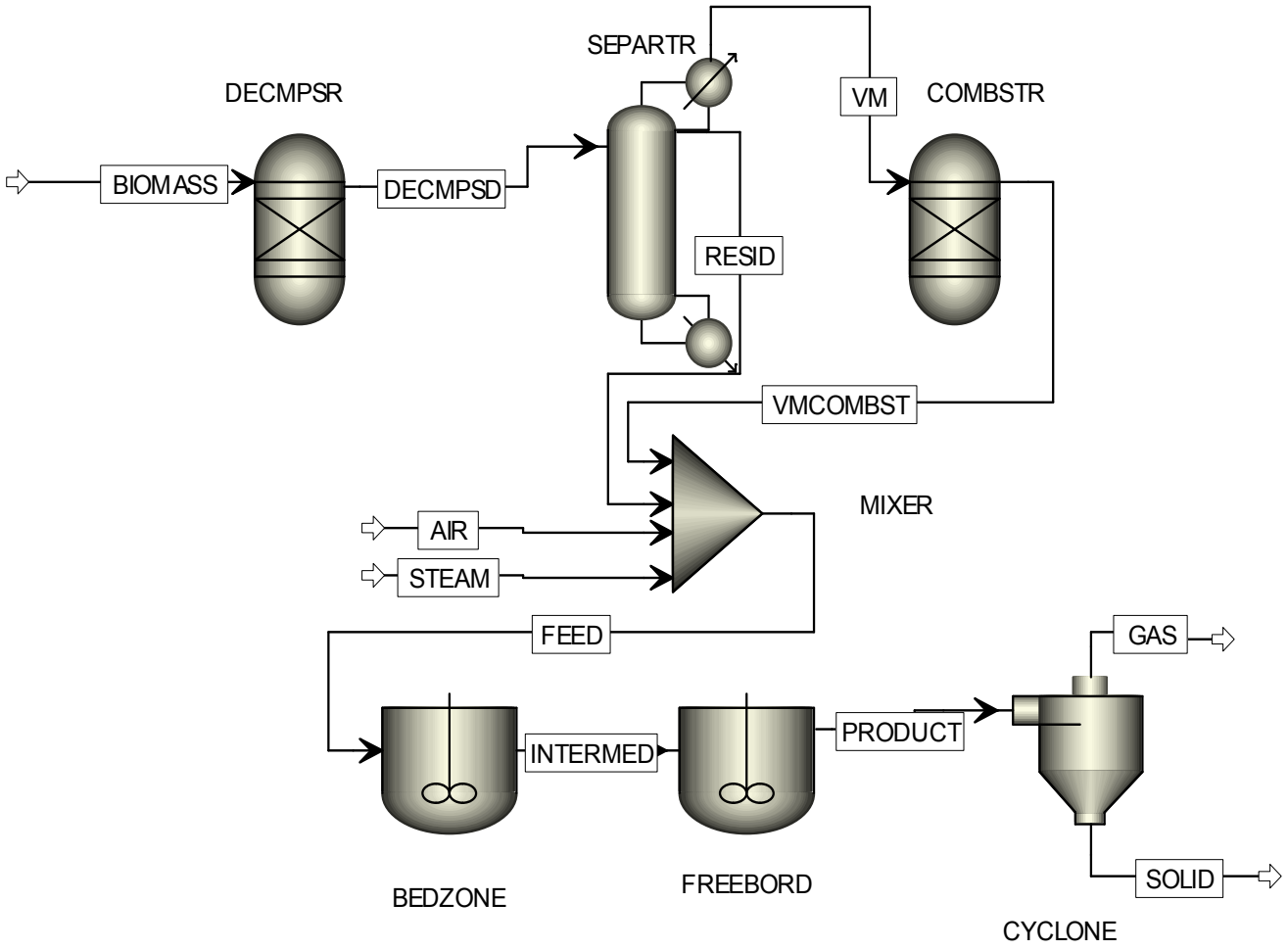


Figure1: Simulation flow-sheet of fluidized bed gasification used in ASPEN PLUS.

3.5 SIMULATION MODEL ANALYSIS

3.5.1 Effect of Variation of Steam Flow (at lower flow rates and higher steam to biomass ratios) on Product Gas Composition.

Air flow rate = 0.1 m^3/hr; Biomass flow rate = 0.1 kg/hr; temperature = 1000 ^{0}C

Table 6: Product gas composition variation with steam flow rates

Steam (kg/hr)	S/B	H_2 (%)	CO (%)	CO_2 (%) (*10^4)	CH_4 (%)
0.08	0.8	12.34	18.4	4.43	6.23
0.1	1.0	11.45	17	4.10	5.8
0.2	2.0	8.3	12.5	3.10	4.2

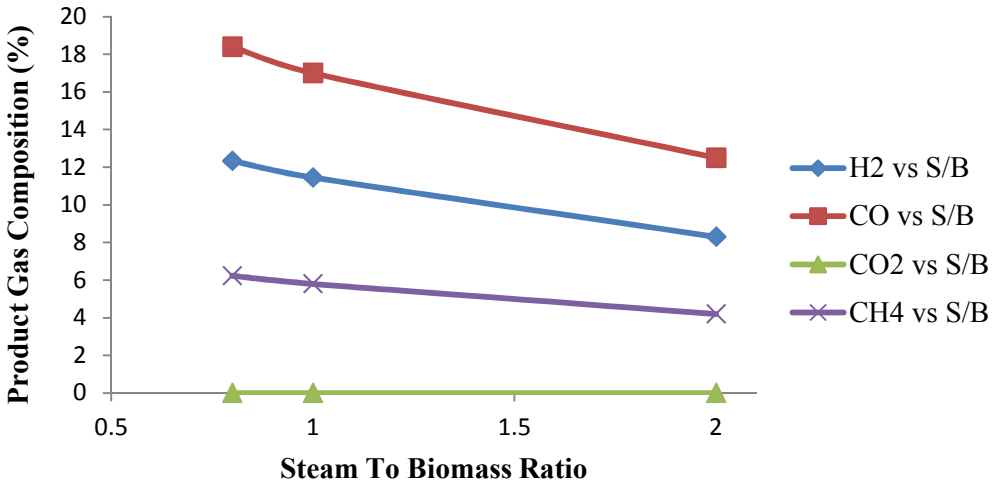


Figure 2: Plot of product gas composition versus steam to biomass ratio

3.5.2 Effect of Variation of Steam Flow (at comparatively higher flow rates and lower steam to biomass ratios) on Product Gas Composition.

Air = 0.1 m^3/hr; Biomass = 1.8 kg/hr; temperature = 1000 ^{0}C

Table 7: Dependency of product gas composition on steam flow rate

Steam(kg/hr)	S/B	H_2 (%)	CO (%)	CO_2 (%)(*10^4)	CH_4 (%)
1.08	0.6	18.4	27.4	7	9.27
0.72	0.4	20.8	31	7.5	10.49
0.36	0.2	24	36	8.6	12
0.18	0.1	26	38.6	9.3	13

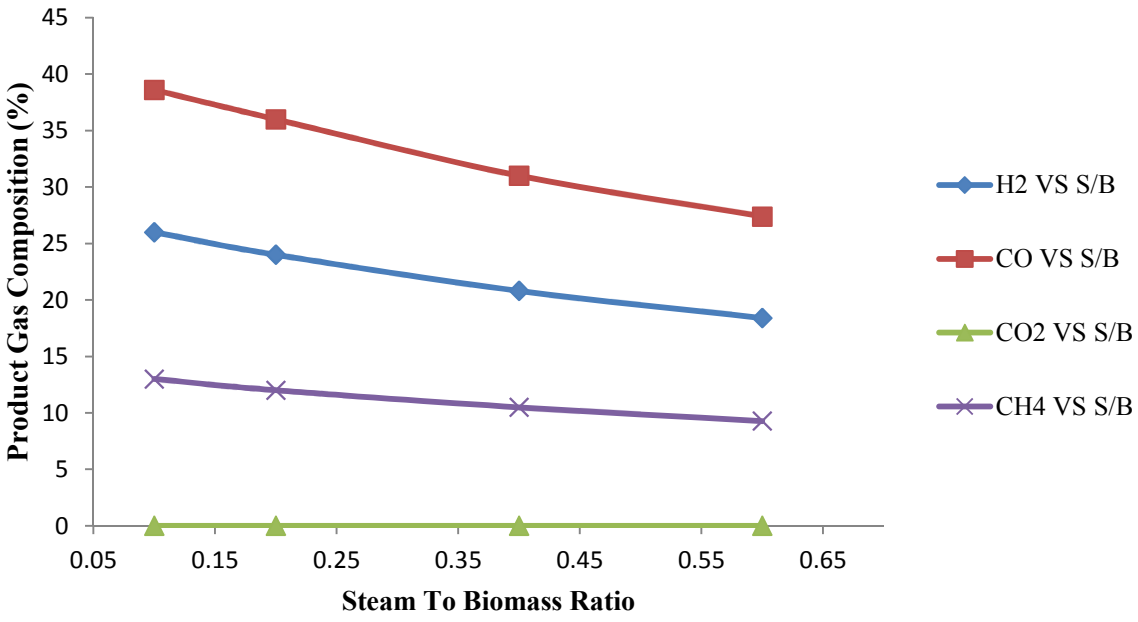


Figure 3: Plot of product gas composition versus higher steam to biomass ratios

3.5.3 Effect of Air Flow Rate at Constant Steam to Biomass Ratio on the Product Gas composition.

(Steam/biomass) = 0.1; Steam = 0.18 kg/hr; Biomass =1.8 kg/hr; Temperature = 1000 ^{0}C

Table 8: Product gas composition variation with air flow rate

Air (m^3/hr)	H_2 (%)	CO (%)	CO_2 (%)	CH_4 (%)
0.05	26.33	39.2	9.45*10^(-4)	13.28
0.10	26	38.6	9.30*10^(-4)	13
0.20	25	37.5	9.02*10^(-4)	12.69

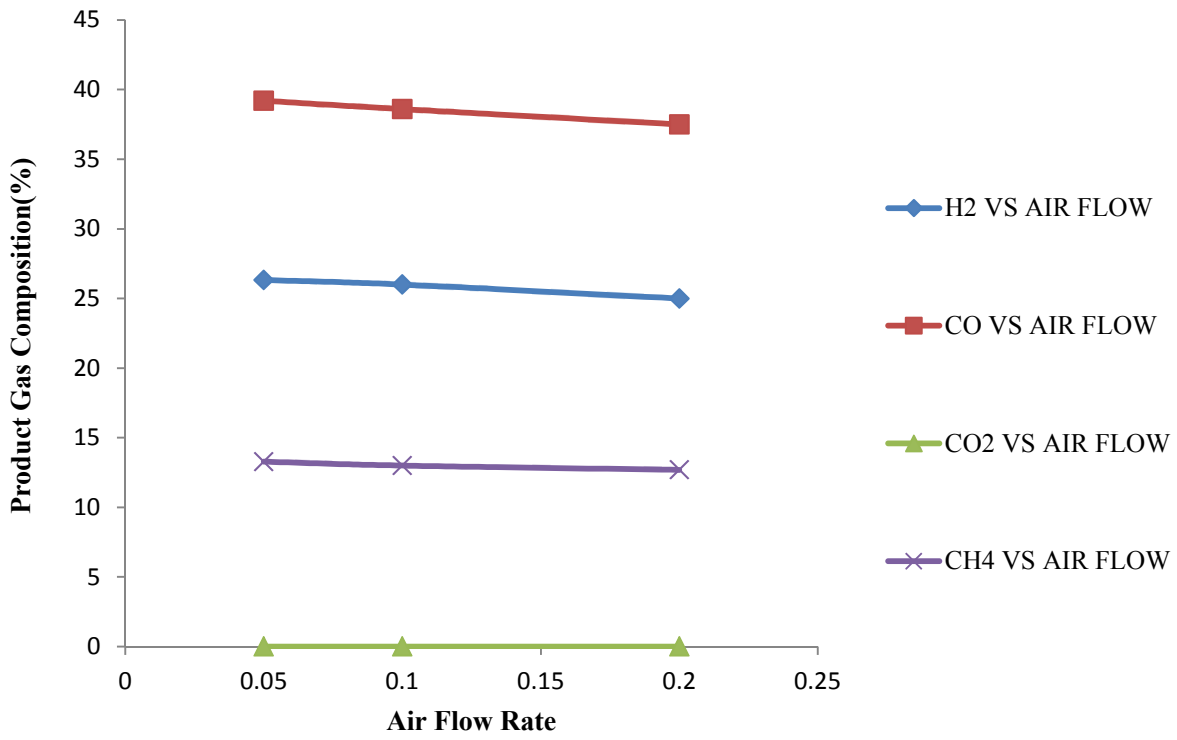


Figure 4: Plot of product gas composition versus air flow rate

3.5.4 Effect of Temperature at Constant Steam to Biomass Ratio and Air Flow Rate on Product Gas Composition.

S/B = 0.1; air flow rate = 0.05 m^3/hr

Table 9: Variation of product gas composition with temperature

Temperature (^{0}C)	H_2 (%)	CO (%)	CO_2 (%)	CH_4 (%)
700	23.5	37.7	1.17	15.34
800	26.0	39.1	0.00875	13.46
900	26.31	39.2	0.00758	13.3
1000	26.33	39.22	0.00945	13.28
1100	26.34	39.22	0.00016	13.29

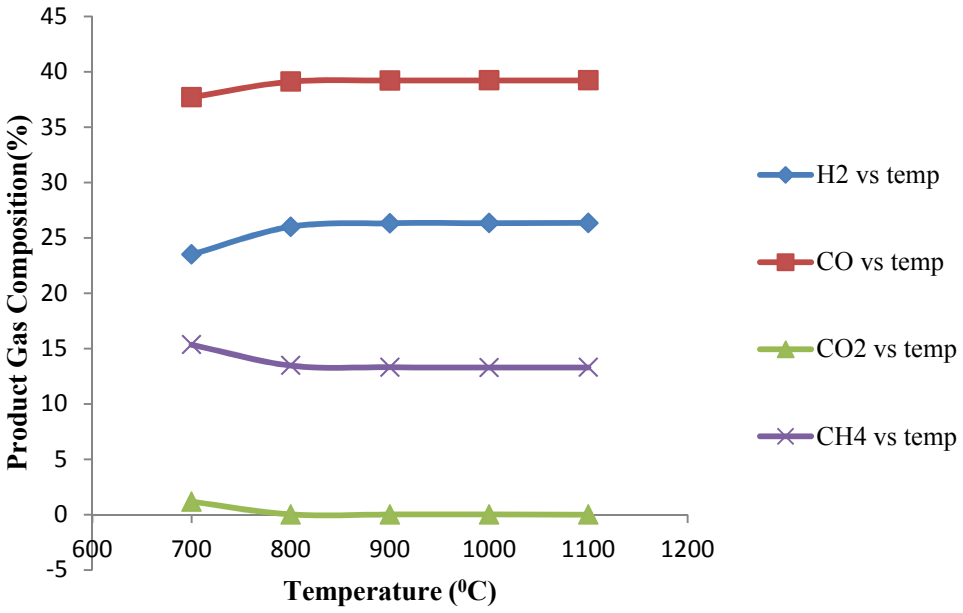


Figure 5: Plot of product gas composition versus temperature

3.5.5 Effect of Equivalence Ratio on Product Gas Composition and Carbon Conversion Efficiency.

(Steam/biomass)= 0.2; Biomass = 3 kg/hr; Steam = 0.6 kg/hr; Temperature = 1000 ^{0}C

Table 10: Dependency of product gas composition and carbon conversion efficiency on equivalence ratio

Eq. ratio (ER)	H_2 (%)	CO (%)	CO_2 (%) (*10^4)	CH_4 (%)	CARBON CONVERSION EFFICIENCY (%)
0.18	21	31.24	1.27	10.6	85.2
0.21	20.5	30.48	1.24	10.32	87.32
0.24	20	30	1.21	10.08	89.75
0.27	19.52	29.07	1.19	9.85	71.45
0.30	19.08	28.4	1.16	9.62	71.24

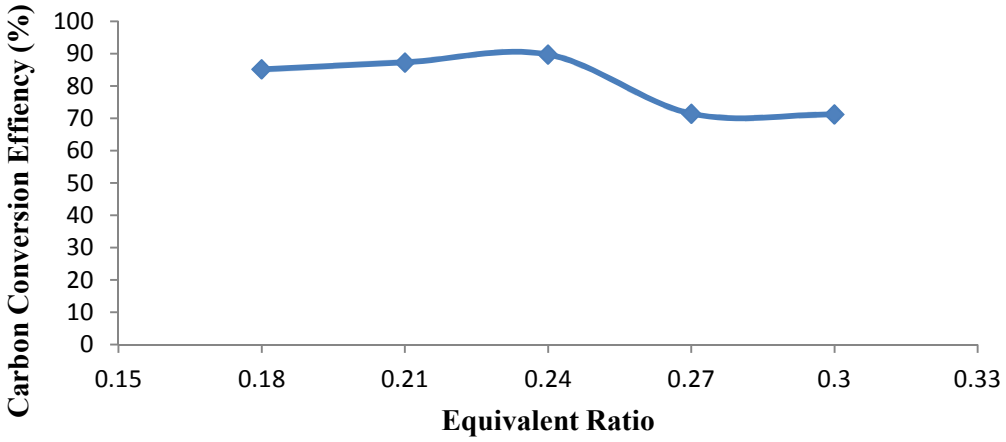


Figure 6: Plot of carbon conversion efficiency versus equivalence ratio

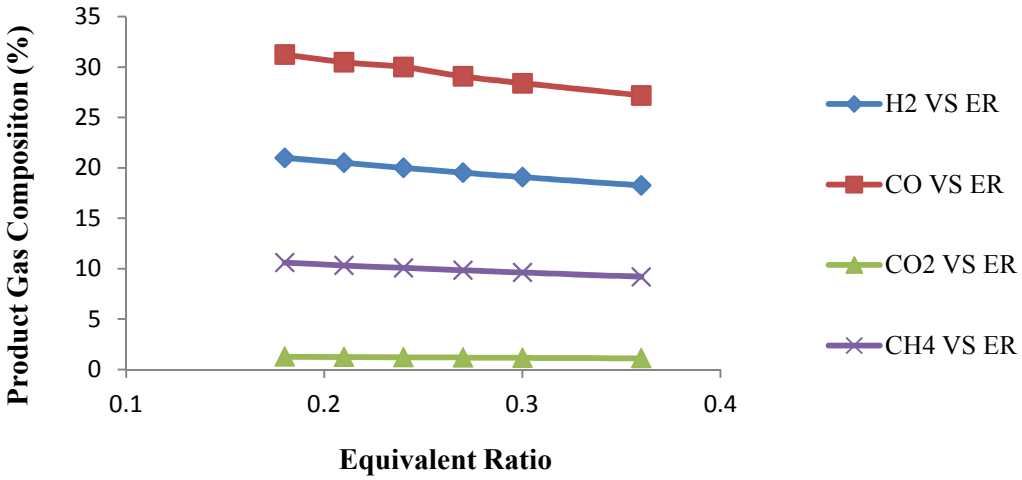


Figure 7: Plot of product gas composition versus equivalence ratio.

3.5.6 Effect of Pressure on Product Gas Composition

Air = 1 m^3/hr; steam = 0.6 kg/hr; biomass = 3 kg/hr; S/B = 0.2, temperature-1000 ^{0}C

Table 11: Pressure variation resulting in change of product gas composition

Pressure (atm)	H_2 (%)	CO (%)	CO_2 (%)(*10^4)	CH_4 (%)
1	21.08	31.4	1.2	10.64
2	18.41	27.43	4.17	9.3
3	16.34	24.35	8.31	8.25
4	14.69	21.89	13.7	7.42
5	13.34	19.88	18.8	6.74

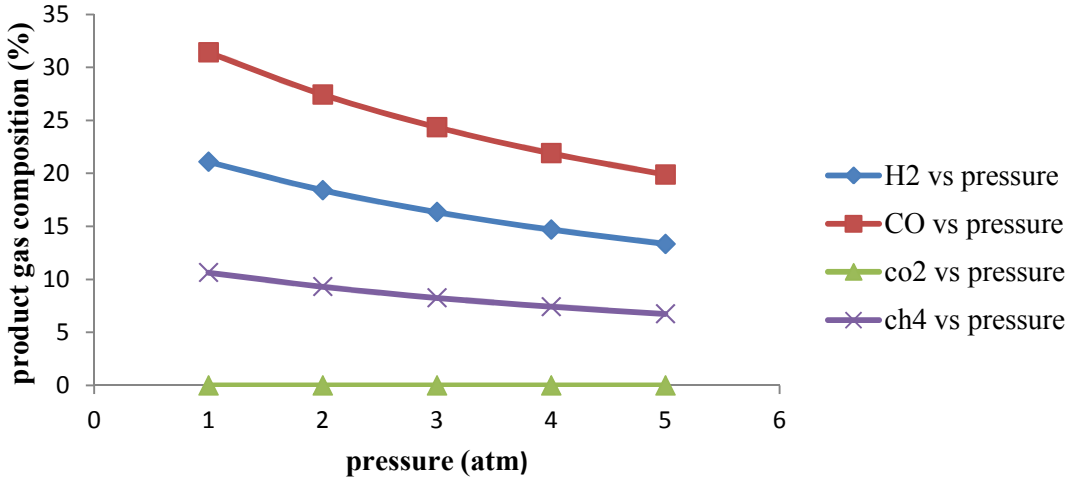


Figure 8: Plot of product gas composition versus pressure variation

3.5.7 Effect of Steam to Biomass Ratio on Carbon Conversion Efficiency.

Equivalence ratio = 0.24; temperature = 1000 ^{0}C; Biomass flow rate = 3 kg/hr

Table 12: Variation of carbon conversion efficiency with respect to steam to biomass ratio

Steam to Biomass Ratio	Carbon Conversion Efficiency (%)
0.2	71.27
0.5	71.14
0.8	71.25
1.1	71.06
1.4	71.27

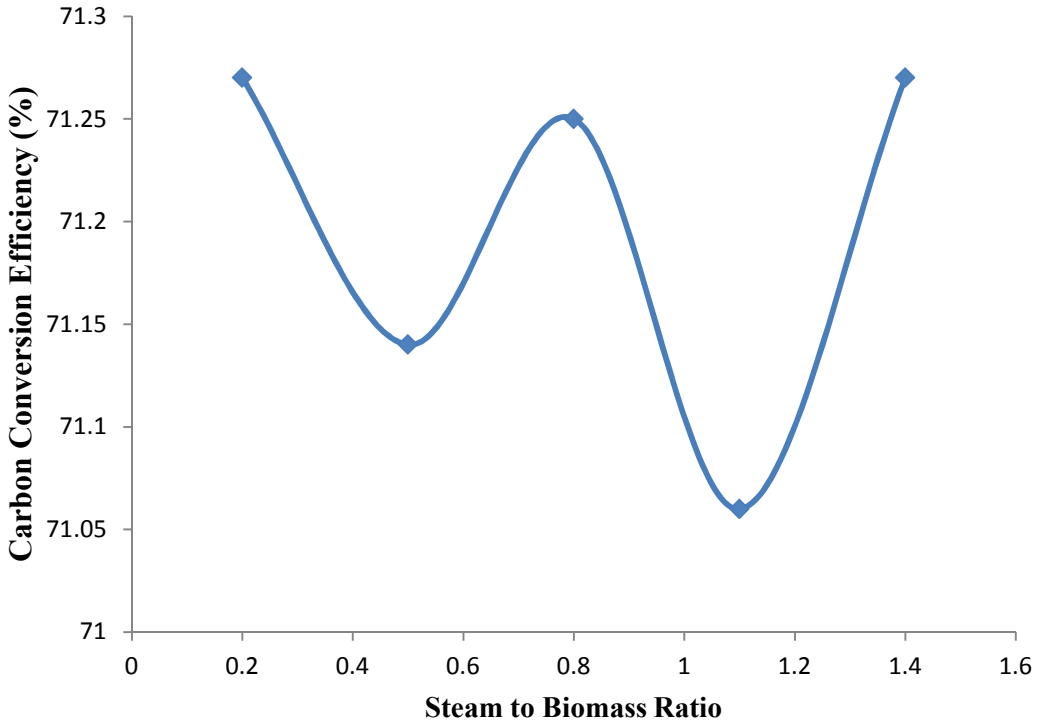


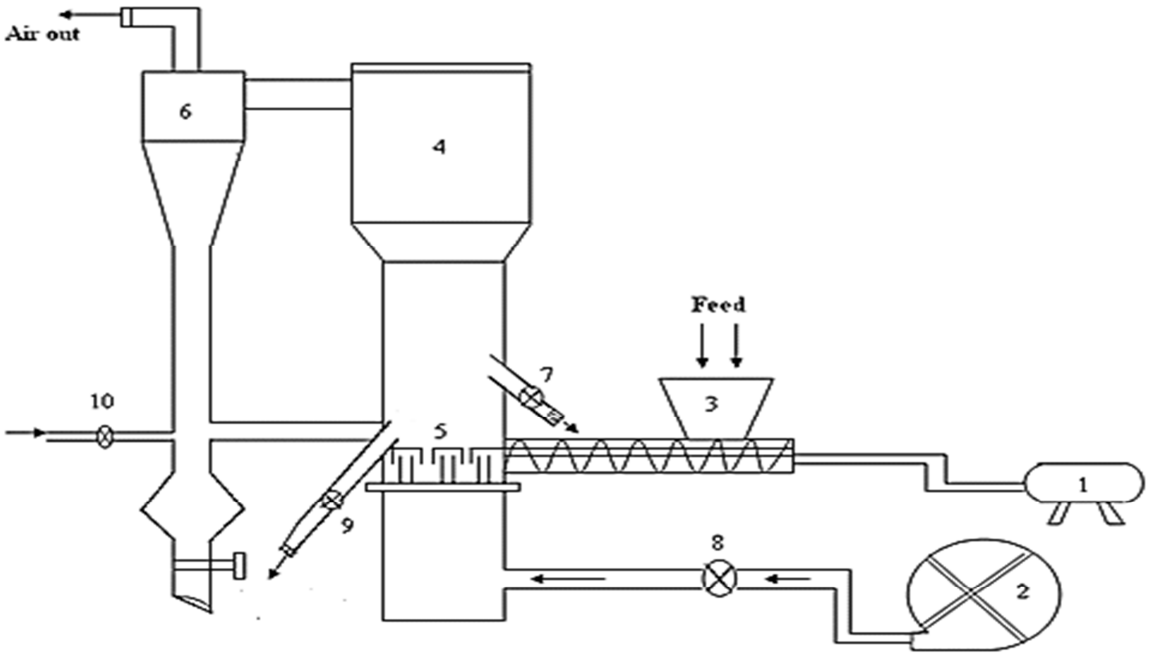
Figure 9: Plot of variation of carbon conversion efficiency with steam to biomass ratio

CHAPTER 4

EXPERIMENTATION

EXPERIMENTATION

The experimental set up consists of a Cold Model and Hot Model Gasifier. The work for the present report was carried out in the cold model unit only because of the time constraint. In the cold model unit, the hydrodynamic characteristics of bed materials were studied which are to be used in the real mode i.e. hot model unit of gasification. The pressure drop and minimum fluidization characteristics were determined for the different biomass samples with different bed materials in the cold model unit and then using these values as operating conditions for the hot model unit, the actual gasification reaction is to be carried out. Finally the compositions of the product gas from the Hot Model unit are to be determined. In the present case the experimentation basically is restricted to the study of bed hydrodynamic characteristics in the Cold Model unit of fluidized bed gasifier.



1.	Pump	6.	Cyclone separator
2.	Air blower	7.	Biomass out
3.	Screw feeder	8.	Valve
4.	Fluidized bed reactor	9.	Bed material out
5.	Bubble cap	10.	Valve

Figure 10: The schematic diagram of the Cold Model

Figure 11: Gasifier cold model in laboratory

Figure 12: Gasifier hot model in laboratory

4.1 OPERATING PROCEDURE

A fixed quantity of bed material is taken in the screw feeder and the time taken for feeding is noted till it attains a minimum height inside the fluidized bed reactor i.e. around the bubble cap. The feeding rate is measured and air is supplied from the blower. The pressure drop across the bed, at the inlet, at minimum fluidization conditions and turbulent conditions are noted with a particular height of the bed. Then the time is measured for each 1.0 cm increase in the bed height and the same procedure is repeated till the entire feeding material is emptied from the screw feeder into the fluidized bed reactor.

4.2 TERMS AND DEFINITIONS

- **Minimum fluidization velocity:** The minimum velocity of a fluidizing agent which when passes through the interstices of a bed of solids creates disturbance as if the weight of the solid bed is being counterbalanced by the force of buoyancy. At this point the entire solid bed moves like a fluid and the velocity of fluid at this point is called minimum fluidization velocity.

$$U_{mf} = \frac{d_p^2(\rho_p - \rho_f)g \times \epsilon^3 \times \varphi^2}{150.\mu(1-\varepsilon)} \qquad (9)$$

- **Terminal Velocity:** An object is said to be moving at terminal velocity when the force of gravity balances the force of drag. At this point the object stops accelerating and continues to fall at a constant speed called terminal velocity.

$$U_t = d_p \left[\frac{4(\rho_p - \rho_f)^2.g^2}{225.\rho_f.\mu}\right]^{1/3} \qquad (10)$$

4.3 PROPERTIES OF DOLOMITE

Table 13: properties of dolomite sample in the experiment

Properties	Values
Particle diameters (d_p)	1.193mm,2.18mm,2.58mm
Density of particle (ρ_p)	2860 kg/m^3
voidage (ε)	0.4
Sphericity (φ)	0.75

4.4 OPERATING CONDITIONS OF AIR

Temperature: 25 ^{0}C

Density of air: 1.167 kg/m^3

Viscosity (μ): 0.000018 kg/ms

4.5 EXPERIMENTAL ANALYSIS

- **Sample1: Dolomite; Particle diameter: 1.193 mm**.

Table 14: Bed hydrodynamics study of sample 1 dolomite

Bed Height (cm)	Minimum Fluidization		Fluidization velocity (m/sec)	mass flow rate of air (kg/hr)	Turbulent Fluidization	
	Pressure Drop at the inlet (mm H_2O)	Pressure Drop across the bed (mm H_2O)			Pressure Drop at the inlet (mm H_2O)	Pressure Drop across the bed (mm H_2O)
2	125	135	28.3981	58.5223711	200	215
2.5	115	130	27.2385	56.1326864	220	240
3	120	135	27.8243	57.3399791	240	255
3.5	105	115	26.0273	53.6366391	225	245
4	90	100	24.0966	49.6578786	230	245
4.5	95	105	24.7569	51.0186203	210	225
6	40	80	16.0644	33.1052524	155	185

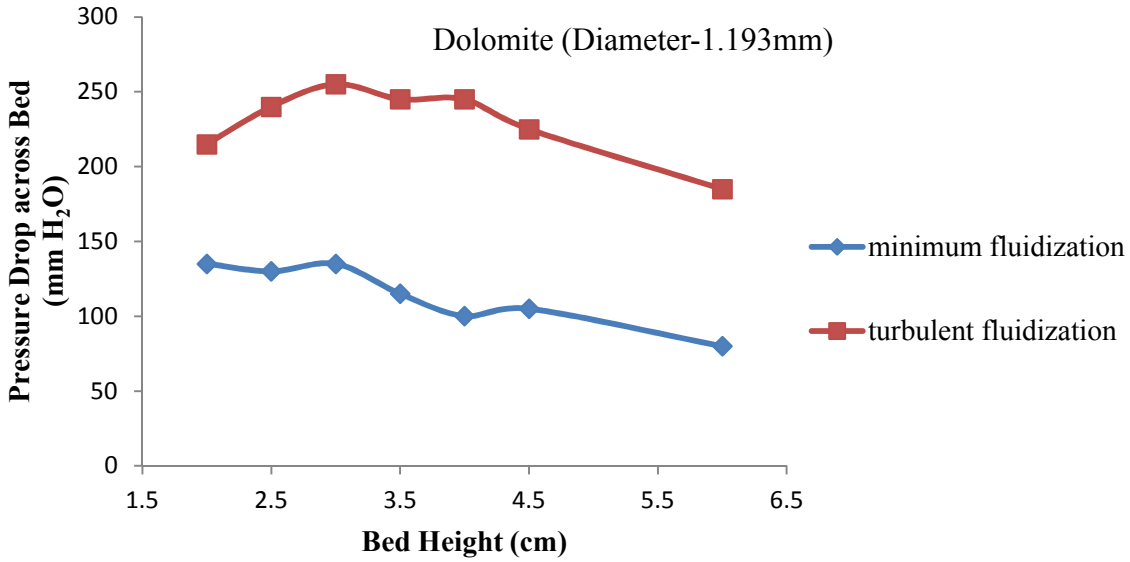


Figure 13: Pressure Drop versus Bed height at minimum and turbulent fluidization conditions for sample 1 dolomite.

➢ **Sample 2: Dolomite; Particle diameter: 2.18 mm**

Table 15: Bed hydrodynamics study of sample 2 dolomite

Bed Height (cm)	Minimum Fluidization		Fluidization velocity (m/sec)	mass flow rate of air (kg/hr)	Turbulent Fluidization	
	Pressure Drop at the inlet (mm H_2O)	Pressure Drop across the bed (mm H_2O)			Pressure Drop at the inlet (mm H_2O)	Pressure Drop across the bed (mm H_2O)
2	120	130	27.82430592	57.3399791	220	230
2.5	90	120	24.09655577	49.65787855	240	255
3	100	125	25.4	52.344	265	270
3.5	85	115	23.41764292	48.25878351	255	285
4	80	90	22.71845065	46.81789689	255	285
4.5	90	100	24.09655577	49.65787855	230	255
6	50	85	17.96051224	37.01279735	160	195
6.5	50	85	17.96051224	37.01279735	160	195

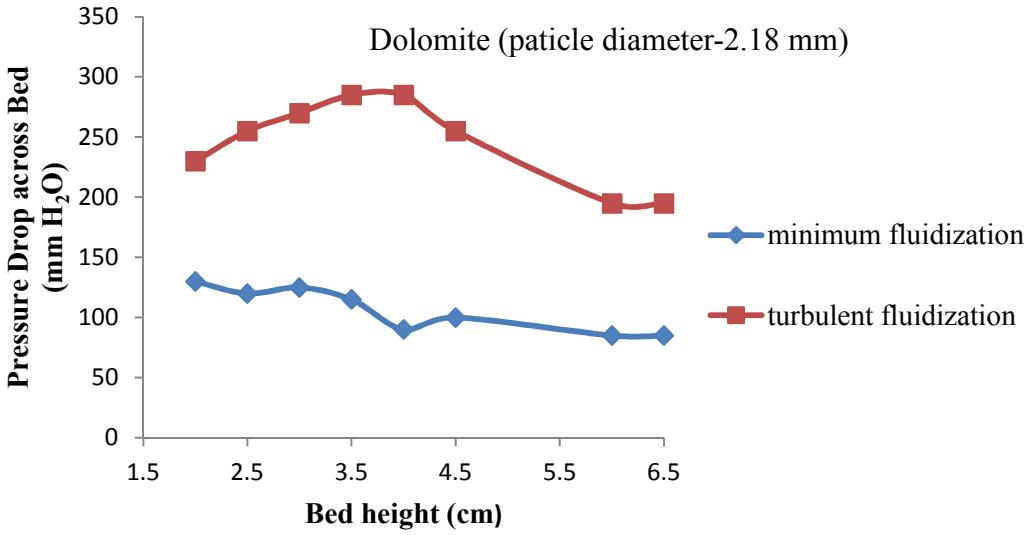


Figure 14: Pressure Drop versus Bed height at minimum and turbulent fluidization conditions for sample 2 dolomite.

➢ **Sample 3: Dolomite; Particle diameter: 2.58 mm**

Table 16: Bed hydrodynamics study of sample 3 dolomite

Bed Height (cm)	Minimum Fluidization		Fluidization velocity (m/sec)	mass flow rate of air (kg/hr)	Turbulent Fluidization	
	Pressure Drop at the inlet (mm H_2O)	Pressure Drop across the bed (mm H_2O)			Pressure Drop at the inlet (mm H_2O)	Pressure Drop across the bed (mm H_2O)
2	135	140	29.5121	60.8182	230	235
2.5	140	150	30.0537	61.9343	235	240
3	145	160	30.5857	63.0305	240	265
3.5	150	155	31.1085	64.108	240	260
4	155	130	31.6227	65.1678	240	260
4.5	115	125	27.2385	56.1327	220	240
6	60	90	19.6748	40.5455	165	190

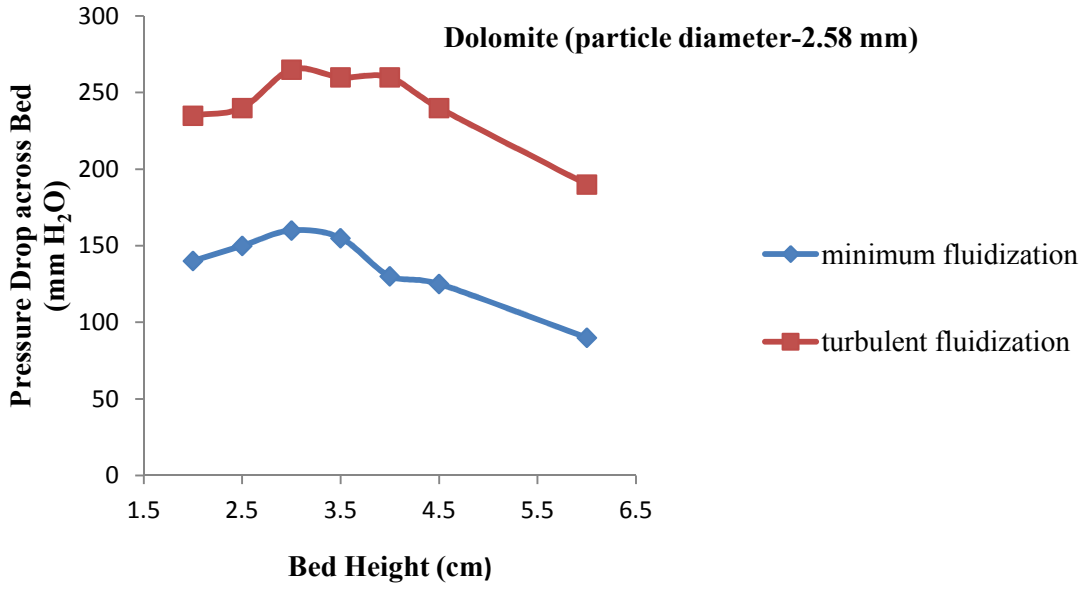


Figure 15: Pressure Drop versus Bed height at minimum and turbulent fluidization conditions for sample 3 dolomite.

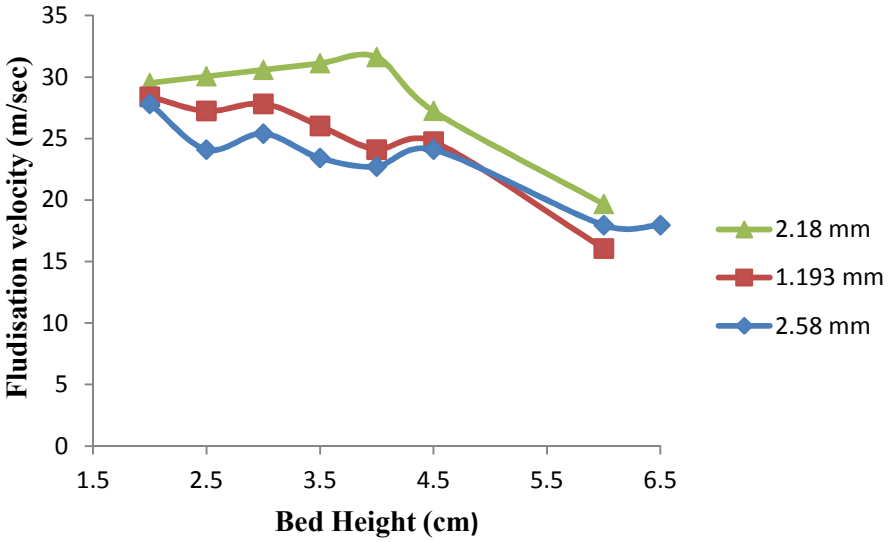


Figure 16: Fluidization velocity versus Bed height

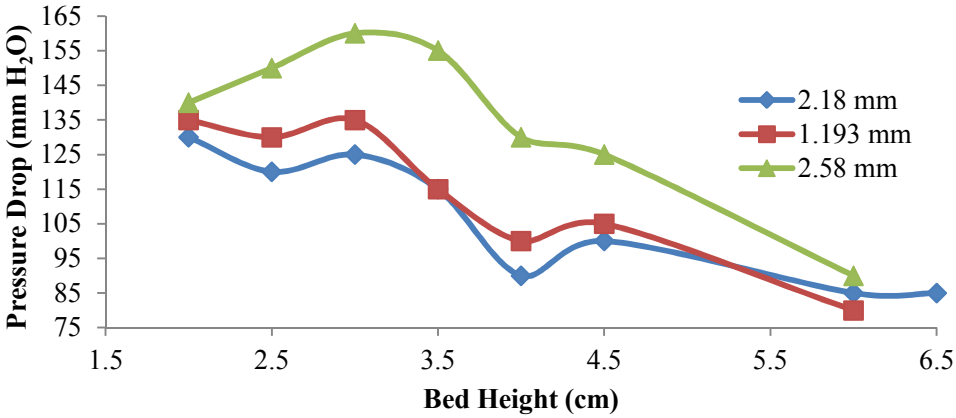


Figure 17: Pressure Drop across the bed versus Bed height.

Table 17: Minimum and terminal fluidization velocities of sample dolomite particles

Dolomite particle diameter(mm)	Minimum fluidization velocity (m/s)	Terminal velocity (m/s)
1.193	0.887	10.42
2.18	2.96	19
2.58	4.15	22.49

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CHAPTER 5
DISCUSSIONS

DISCUSSIONS

The empirical formula of the biomass sample was found to be $CH_{1.68}O_{0.62}$.

$$CH_{1.68}O_{0.62} + 1.11\ O_2 \rightarrow CO_2 + 0.84\ H_2O$$

The effects of pressure, temperature, steam to biomass ratio and equivalence ratio on product gas composition and carbon conversion efficiency were carefully studied. Simulation trials were conducted by varying the steam flow rates thereby changing the steam to biomass ratio whereas the biomass flow rate and all other parameters were kept constant. A decreasing trend in the product gas composition of all the constituents was observed (Table-6, Figure-2) but the decreasing effect was much significant when comparatively higher values of steam were used (Table-7, Figure-3). The extremely low composition of CO_2 can be attributed to the simplifications used in the simulation. The decreasing trend is expected for CO_2 but the reduction in composition of CO may be due to the water gas shift reaction where the CO formed reacts with steam to form CO_2.

The effect of air flow rate was studied on product gas composition (Table-8, Figure-4). As expected the compositions of H_2 and CO started reducing but the reduction wasn't prominent so the effect of air flow in the form of equivalence ratio was analyzed and significant reduction was observed (Table-10, Figure-7). The effect of equivalence ratio on carbon conversion efficiency (Table-10, Figure-6) showed the closest resemblance to the theoretical predictions. Initially when the equivalence ratio is increased the carbon conversion increases but after reaching a maximum a reduction is witnessed which is attributed to the formation of complete combustion products like CO_2 and H_2O rather than CO and H_2. The optimum value of equivalence ratio was found to be 0.23 for maximum carbon conversion.

Temperature has the most profound impact on product gas composition since gasification is a temperature controlled reaction. The gasification reactions being endothermic in nature need high temperature to drive them forward to completion. It was observed that saturation is obtained in the composition of product gas components after 900 ^{0}C (Table-9, Figure-5). The products of endothermic reactions H_2 and CO showed an increasing trend when the temperature was raised but CO_2 and CH_4 showed descending tendencies as they are obtained from exothermic reactions.

On increasing the pressure, CO and H_2 compositions kept on decreasing which indicates that hydrogen is achieved as the main product only when the pressure decreases and atmospheric pressure for hydrogen extraction is used (Table-11, Figure-8).

The variation of carbon conversion efficiency with steam to biomass ratio showed an increase at first then a descending trend and then again an increasing trend (Table-12, Figure-9). The response can be comprehended as with increase in steam flow rate the production of CO would increase at first due to water gas reaction but then shift reaction takes place consuming CO and converting it into CO_2 which would react with char to produce CO again.

On studying the variation of pressure drops across the bed at minimum and turbulent fluidizations it was observed that higher pressure drops are obtained across the bed when there is a shift from minimum to turbulent fluidization (Figure-13,14and15). Dolomite with particle diameter 1.193mm has higher fluidization velocities as compared to the sample with 2.18mm particle diameter because as the diameter increases the void fraction of the bed increases which the reduces the resistance and even by applying less velocity we can fluidize the bed. But when the particle diameter increases further from 2.18mm to 2.58mm the particle weight is not counterbalanced by the buoyant force and hence requires higher fluidization velocity (Figure 16). Hence the fluidization velocities decreases from dolomite (d_p =1.193mm) to dolomite (d_p =2.18mm) but again increases when dolomite (d_p =2.58mm) is used.

In all the above cases it is observed that the pressure drop across the bed follows a steady pattern when the bed height is 4 cm which is approximately 50% of the bubble cap height (Figure 17).

It was observed from table 17 that all the three samples can be fluidized but are not suitable for gasification because they need high fluidization velocities and high mass flow rates of air which might affect the product gas quality in gasification reactions.

CHAPTER 6

CONCLUSION

CONCLUSION

A simulation study using ASPEN PLUS was performed using only the kinetic parameters considering a pine sawdust sample using its proximate and ultimate analysis and the effect of various operating parameters was studied on the product gas composition and carbon conversion efficiency. Various assumptions were incorporated to make the simulation feasible. Some of the results obtained strayed away from the standard pattern due to the absence of a more realistic and rigorous model. However some of the results obtained were quite close to the theoretical predictions. The actual process is a lot more complicated due to tar formation and ash agglomeration which does have an impact on the performance of the gasifier. The steam to biomass ratio was found to be in the range of (0.1-1) for obtaining tangible values of product gas composition. Steam being used in the temperature range of (120-150) ^{0}C should be used at comparatively higher flow rates for steady operation of a gasifier. The temperature should be in a range of (700-900) ^{0}C for making a comparative analysis of composition of various product gas components. The equivalence ratio should be in a range of (0.18-0.24) to obtain high carbon conversion efficiency of (85-89) %. If the ratio is lower than 0.18 that would lead to incomplete gasification and if it is higher than 0.24 then it would lead to formation of complete combustion products like CO_2 and H_2O. Pressure should be close to atmospheric pressure for production of CO and H_2. There is a competition between the several gasification reactions to reach completion so it is very difficult to access the product gas composition as it also depends upon the operating parameters. The purpose of gasification dictates the presence or absence of a gasifying agent. ASPEN PLUS simulator provides a great deal of help in accessing the performance of a unit operation. It gives various insights about optimizing the various process parameters. It also assists in making cost estimations, judging the economy of an operation and making sensitivity analysis while finding out the critical components which mainly affect a process.

Through the bed hydrodynamics study with dolomite as the bed material with different particle sizes it was observed that for the real model application of gasification the particle size of dolomite should be less than 1.193 mm to achieve proper fluidization conditions and maintain the better quality of gasification products.

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